5.1 EXAMINATION OF THE IRRADIATED SUPERCONDUCTING PROPERTIES OF NANOPARTICLE-DOPED $YBA_2CU_3O_{7-X}$ COATED CONDUCTORS FOR FUSION ENERGY APPLICATIONS

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OBJECTIVE

The goal of this work is to evaluate the irradiation response of the newest generation of $YBa_2Cu_3O_{7-x}$ (YBCO) high temperature superconducting (HTS) materials. The task will include the effects of different processing conditions (method of deposition, type of buffers, use of dopants, etc.) on the initial defect structure prior to irradiation and the defect structure changes during irradiation.

SUMMARY

A program is in place to examine the effects of room temperature ion irradiation on the superconducting properties of several YBCO HTS materials that utilize different flux pinning strategies. This will provide a first investigation into both the radiation-induced flux pinning and changes to pre-existing pinning centers. The work will then be expanded to low temperature irradiation testing that will include *in situ* measurement of self-field superconducting properties as a function of dose, with a further analysis into defect annihilation and effects of temperature excursions on conductor properties.

PROGRESS AND STATUS

Background

In an effort to reduce reactor complexity and costs, the ORNL Fusion Materials Program is evaluating the irradiation response of the newest generation of $YBa_2Cu_3O_{7-x}$ (YBCO) high temperature superconducting (HTS) materials for possible qualification in future magnetic confinement reactor designs. In addition to the higher critical temperature over currently used Nb_3Sn (T_c = 92 K versus 18 K for Nb_3Sn), YBCO conductors offer higher critical current density (J_c) values, a smaller flux pinning coherency length that can produce J_c increases on exposure to neutron irradiation up to $1x10^{22}$ n/m^2 (E>0.1 MeV) [1-10] and a smaller effective neutron capture cross section.

Since the appearance of HTS materials and their fabrication into long-length wires, they have been limited to self-field applications such as power transmission due to their low characteristic irreversibility field [11]. The newest generation of YBCO conductors incorporate the use of engineered textured substrates and nanoparticle additions to the conductor to produce correlated defect structures in the YBCO lattice that increase J_c values with reduced dependence on magnetic field. These defect structures can be tailored to specific field applications and have demonstrated increases in J_c by a factor of 6 or more under high magnetic fields [12].

The majority of irradiation studies to date on YBCO have been centered on examining the development of radiation-induced flux pinning defect structures at low irradiation fluences. Little systematic examination of the overall behavior of the material under irradiation exists, or on the effect of different processing conditions (method of

deposition, type of buffers, use of dopants, etc.) on the initial defect structure prior to irradiation and its changes during irradiation. Typically, the YBCO irradiation database consists of testing at or slightly above room temperature and is dominated by materials that are processed by melt-textured or powder processing techniques producing poly- and single-crystal samples, rather than coated conductor wires. For the latter however, ion-irradiated testing has primarily involved swift heavy ions (100 MeV to several GeV) in order to generate long columnar defect structures similar to those created by the incorporation of nanoparticles into the YBCO films [013-17]. The use of low energy ions (0.5 to 25 MeV) is more representative of the defect cascades produced by neutron irradiation [18-20].

The goal of this work to evaluate the irradiation response of several types of the latest generation of YBCO coated conductors that incorporate nanoparticle additions into their microstructure for enhanced flux pinning and improved performance in externally applied magnetic fields. The samples chosen will represent different methods for flux pinning related to the defect structures produced in the YBCO and will examine the HTS materials response to irradiation damage. Ion beam irradiation will be used to simulate neutron damage cascades in the YBCO and buffer layers, allowing for simplified post-irradiation characterization.

In the first year we plan on investigating the effect of room temperature irradiation on both the radiation-induced flux pinning response as well as examining the induced changes to pre-existing pinning centers. This will allow the establishment of the overall response of the materials to different ion energies and fluence. This work will continue to low temperature ion-irradiation tests over specific energy ranges and fluence including *in situ* measurements of self-field superconducting properties as a function of dose. The low temperature irradiations will also allow for studies on defect annihilation as well the effects of temperature excursions on conductor properties.

Materials

The YBCO films to be examined are based on the highest J_c performing coated conductor technologies. Table 1 lists the materials selected for testing. The coated conductors consist of biaxial textured YBCO films (1.0-1.5 μm thick) deposited by metalorganic chemical vapor deposition (MOCVD) onto buffered Ni-alloy tapes. The biaxial texturing of the YBCO needed for the flow of current along the length of the tape is generated from either the rolling assisted bi-axial textured metallic substrate or developed within the buffer layer. Examples of the two tape architectures used in this study are illustrated in Figure 1. The addition of different dopants to the MOCVD films result in the development of nanoparticles, sometimes referred to as nanodots, that improved angular and field dependent J_c values resulting from the alignment of these nanodots, the defect structures generated by them or the combined effect of defect and particle. Addition of Zr in the MOCVD processing of YBCO forms self-assembled $BaZrO_3$ nanodots that are aligned in a columnar fashion along the c-axis direction, producing superior performance over baseline films primarily at orientations corresponding to the magnetic field parallel to the c-planes, or H//c. The addition of Dy aids in the development of $(Dy,Y)_2O_3$ particles as well as promotes $YBa_2Cu_4O_8$ intergrowths (additional Cu-O layers in the YBCO stacking) that increase H//ab pinning. Enhanced pinning in both the H//c and H//ab conditions is produced in Nb-doped YBCO through the development of a three-dimension defect structure of c-axis aligned YBa_2NbO_6 particles and faulted defect structures in a- and b-directions. Comparison of

the enhanced pinning YBCO films to plain YBCO on SuperPower substrate will be examined.

Table 1. List of the YBCO and substrate conditions to be tested, the type of pinning features created, and the status of the work to date.

YBCO additive	Substrate	Pinning Effects	Status
Zr	SuperPower	$BaZrO_3$ nanodots aligned along the c-axis direction, producing enhanced H//c pinning.	Material undergoing pre-irradiation characterization.
Dy	American Superconductor	$(Dy,Y)_2O_3$ nanoparticles, enhanced H//ab pinning from increased $YBa_2Cu_4O_8$ intergrowths.	Material undergoing pre-irradiation characterization.
Nb	SuperPower	YBa_2NbO_6 nanoparticle alignment in c-axis direction, for enhanced H//c pinning, in addition to increased H//ab pinning from defects generated.	Material to be fabricated.
None	SuperPower	No additional pinning defects, other than those generated at buffer interface creating stacking faults within the YBCO.	Materials to be fabricated.

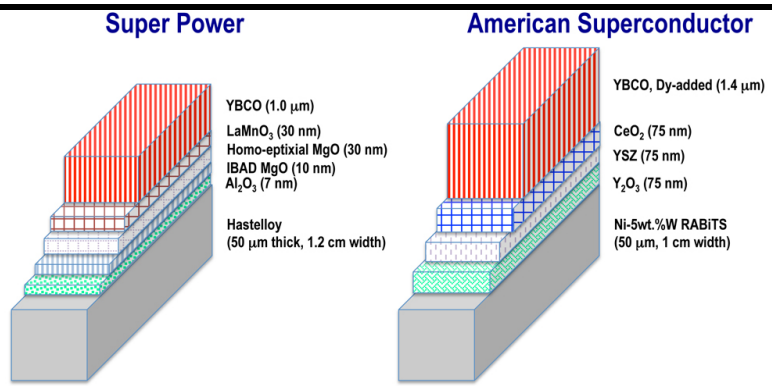

Figure 1. Illustration of the two types of coated conductor tape architectures used in this work.

Pre-Irradiation Characterization

Characterization of the pre-irradiated electrical properties of the Zr-YBCO and Dy-YBCO samples has begun. The Zr-YBCO tape was purchased directly from SuperPower Incorporated, while American Superconductor Corporation provided the Dy-YBCO for this work. Un-doped YBCO and Nb-YBCO tapes will be fabricated at ORNL at a later date on the SuperPower buffered tape architecture. The long-length Zr- and Dy-YBCO conductors showed critical current, I_c, values in self-field of approximately 239 A/cm-width and 525 A/cm-width, respectively. The tapes have been cut down into smaller test samples and for the case of the Zr-YBCO material, the Ag overlay coating was removed through etching. Patterned current bridges were laser scribed into the YBCO for electrical characterization tests. Silver was deposited at specific sites for the pad positions of the four-probe voltage and current contacts. Following this, the samples

were given a thermal anneal in oxygen at 500°C for 1 hour. The initial bridge pattern, version 1 shown in Figure 2, which was selected for electrical characterization, was found to be susceptible to shorting caused by Ag not removed from the edges of the sample following etching in addition to tolerance related issues associated with the laser scribe. The version 1 shown in pattern is a standard bridge design that eliminates the effects of stress and localized heating in the YBCO at the probe positions. A simplified bridge pattern, version 2, was employed to avoid the problems related with the more complex pattern.

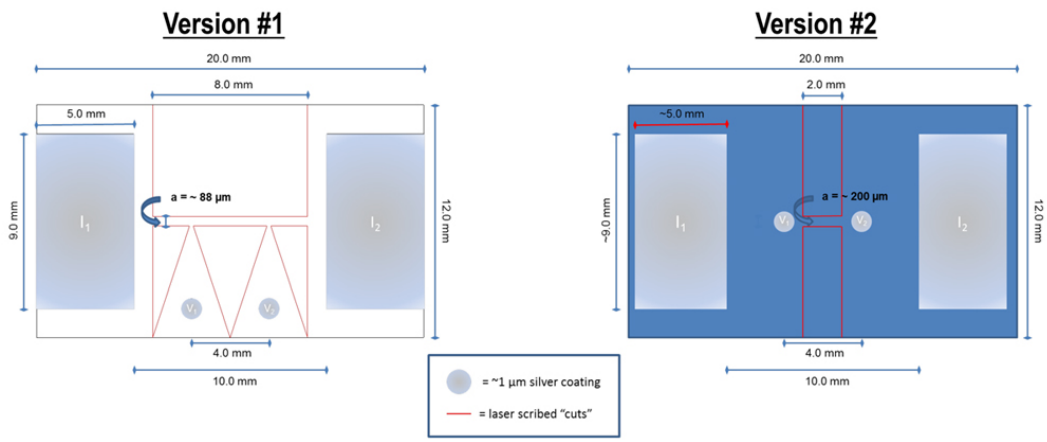

Figure 2. Versions of the bridge design for testing the high I_c doped-YBCO samples. Version 1 was found to be problematic due to electrical shorting and replaced with the simplified version 2.

Field dependence characterizations of J_c as a function of applied magnetic field strength, and resistance versus temperature are now being performed on both the Zr-YBCO and Dy-YBCO series of samples at the University of South Alabama. Angular dependence of I_c with field is being measured at ORNL. An example of the data being collected is shown in Figure 3, for a sample of the Zr-YBCO film on SuperPower tape architecture. Pre-irradiation characterization will allow for the precise assessment of each samples response to irradiation. Further detailed information on sample testing, tape performance and microstructural characterization in the pre-irradiated condition will be provided at a later date.

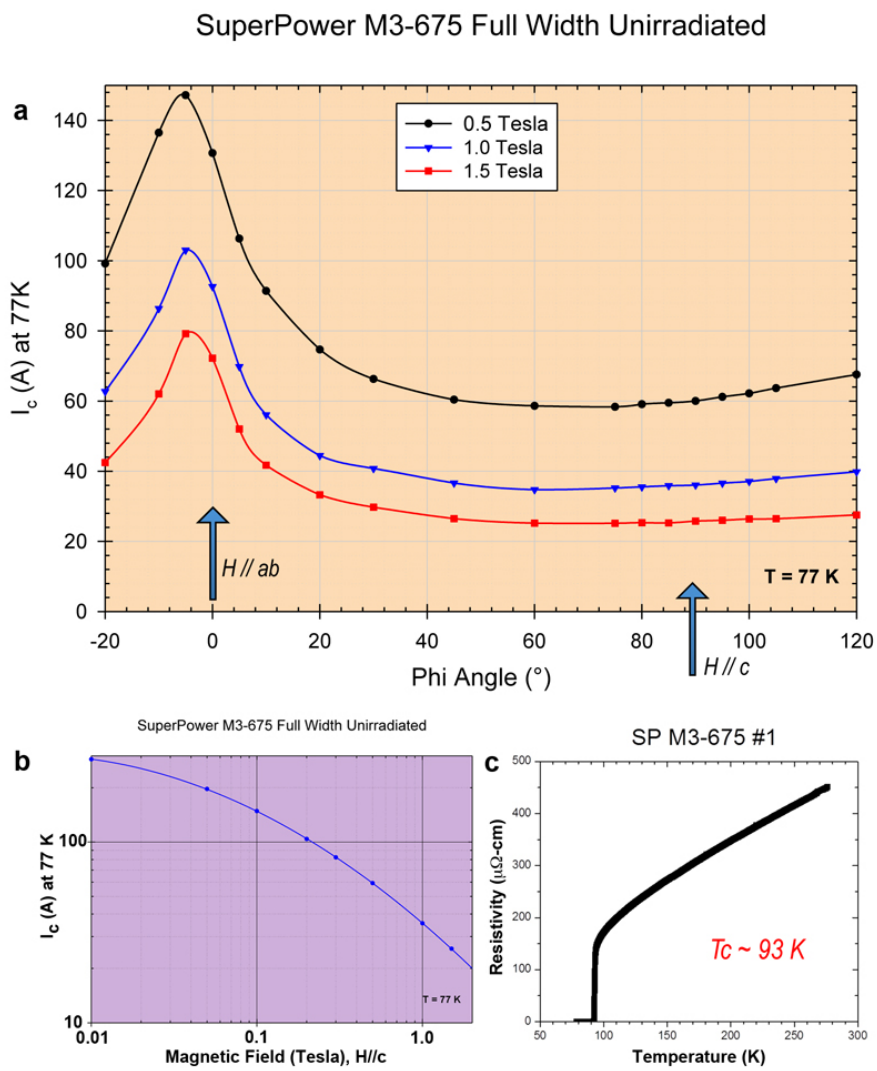

Figure 3. Preliminary data for Zr-YBCO film on SuperPower buffered tape architecture. (a) Angular dependence of critical current on the applied field at different field strengths, (b) critical current as a function of applied field at H//c, and (c) the resistivity versus temperature curve showing the transition temperature, T_c = 93 K.

Ion Irradiation Testing

Ion irradiation will be used as effective approach to evaluate materials performance in neutron irradiation environments. Irradiation of the short segments of coated conductor tapes will be performed at the University of Tennessee Ion Materials Laboratory (UT-IML). The facility, which is operational but completing final construction, will be equipped with two ion sources, three beam lines and three end stations providing the capability irradiation of ions from H to Au with energies ranging from a few keV to ~25 MeV, depending on ion and current required.

Ion irradiation of the MOCVD YBCO conductors will be performed at lower energy levels typical of simulating cascade damage to avoid columnar defect formation that is typically observed by higher energy heavy ion irradiations (in the hundreds of MeV region). In order to produce defect cascades similar to that observed in neutron irradiations, the electronic energy loss of the irradiating ions will need to be less than that of 20 keV/nm based on previous work [18, 21, 22].

To examine physical property changes over the unirradiated materials, irradiation by ions in the high keV - low MeV energy range, fluences between 10^{11} to 10^{14} ions/cm^2 will be likely [21]. Computational analysis of energy loss profiles through the HTS tapes was performed using TRIM calculations to evaluate the optimum dose rate, fluence, ion energies and penetration depth. Three ion energies that are being considered for this study are 10 MeV oxygen, 25 MeV copper, and 25 MeV gold, with examples of the ion ranges, energy loss and collision profiles as a function of depth into the sample are shown in Figure 4. Ion penetration depths will be into the Ni-alloy substrates to avoid the introduction of impurities that may create the introduction of unintentional artifacts measured in the conductor properties.

SUMMARY

The ion-irradiation examination of these films follows a significant multi-decade development of both optimized buffered tape technology and research into increased flux pinning response of HTS films. This latest generation of HTS conductors offers improved in-field properties that can be tailored to suite specific magnetic field conditions. It is the objective of this study to investigate radiation effects on these materials and assess their suitability for potential applications in fusion environments. This investigation will be one of the first irradiation experiments on nano-doped YBCO coated conductors. The objective of this work is to examine the effect of room temperature ion irradiation on the superconducting properties of several HTS materials utilizing different flux pinning strategies in YBCO. To provide a first investigation into both the radiation-induced flux pinning and changes to pre-existing pinning centers. This will then be expanded to low temperature irradiation testing that will include *in situ* measurement of self-field superconducting properties as a function of dose, with a further analysis into defect annihilation and effects of temperature excursions on conductor properties.

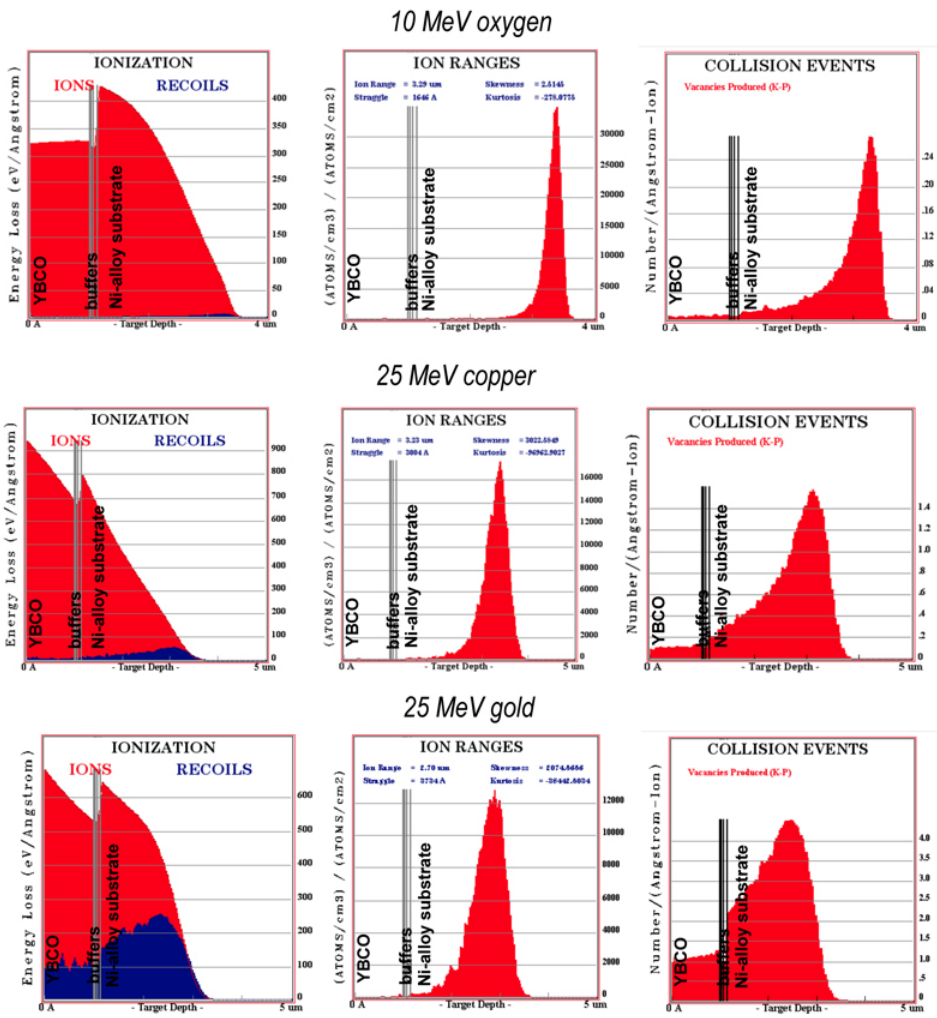

Figure 4. Examples of the energy loss, ion ranges and collision events as a function of target depth produced from TRIM calculations for 10 MeV oxygen, 25 MeV copper and 25 MeV gold ion irradiations of YBCO conductors on SuperPower substrates.

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